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SEISMIC EVALUATION OF SKEW BRIDGE WITH FRICTION TYPE RUBBER BEARINGS - EXPERIMENTS AND CASE STUDIES

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ABSTRACT

The seismic response of the skew bridges with rubber bearing is studied. In Taiwan, simply-supported PCI bridges are widely used with rubber bearing pads as a supporting system. It is common seen that, during the construction practice, the rubber bearing pads have been laid on the cement mortar-made bearing pads without any details of bolting design. This kind of arrangement potentially allows rubber bearing to slide, so as the superstructure when the earthquake occurs. In addition, bridges are usually being skewed to provide transportation service, requiring a further investigation of seat width to avoid falling of the superstructure. In this study, firstly, a series of friction coefficient was conducted. Furthermore, a scale-down skew bridge model has been constructed to perform the shaking table test. According to the experimental results, the inertial forces from superstructure can be reduced because of the sliding-induced isolation effect. The analytical program, SAP2000N was used to simulate the experimental results, and it has been shown the numerical model can predict the acceptable displacement demand. Based on the parametric study, finally, the study will discuss the bridge behaviors with different skew angles and input directions of time histories.

Introduction

A devastating earthquake with a magnitude of 7.6 struck the central region of Taiwan in the early morning of September 21, 1999. It was known as the 921 or Chi-chi earthquake (NCREE 1999). There are approximately 1,100 highway bridges spread on the provincial and county routes in the region. Most of the bridges have simply- supported, reinforced or prestressed concrete slab-and-girder superstructures with rubber bearing pads as a supporting system. About 90 percent of them escaped from serious damage. In the review of the bridge damage caused by the Chi-Chi earthquake, most of the damage appeared to be as a result of the movement of the superstructure and the separation of the thermal expansion joints due to sliding or displace of the bearings (as shown in Fig. 1), with the exception of seven bridges which collapsed due to a large fault displacement cutting directly across the location of the bridge. It was also observed that the number

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of bridge columns that were severely damaged was surprisingly small. Chang et al. (Kuo et. al 2002) developed a bridge model to simulate slide-friction of rubber bearings, impact effect between shear key and girder, and plastic hinge at the end of the columns, providing well simulation on a bridge that was damaged in the Chi-Chi Earthquake. Since most of the bridges in the damaged area caused by Chi-Chi earthquake were designed without ductile detailing, it may be in contrast to the current seismic design concept emphasizing the design of plastic hinges. Besides, damages of skew bridges were also found in the Loma Prieta earthquake (M7.0) in 1989, Northridge earthquake (M6.7) in 1994, Kobe earthquake (M7.2) in 1995. However, studies of skew bridge with rubber bearing are seldom discussed. Besides, considering the route selection, engineers may face to design a skew bridge rather than a regular or straight bridge in some occasions. For example, the bridge which is across the river often has no choice but to make a column bent inclined to the axis of the superstructure. Therefore, this paper presents the experimental study on seismic performance of skew bridge with friction/sliding RB bearing (steel-reinforced elastomeric bearing) and PTFE-RB bearing (steel-reinforced elastomeric bearing coated on a thin PTFE material). The friction coefficient test was carried out first to get friction coefficient of RB bearings and PTFE-RB bearings on the surface of cement mortar, concrete, and steel plates. Two scaled bridge model was utilized in the shaking table test to understand the influence of sliding behavior of bearings on a straight and skew bridge, respectively. The force equilibrium relationship between inertial force and base shear was verified from the test results, helping to build up reasonable analytical models to perform the parametric study. The analytical program, SAP2000N, have been used to simulate the experimental results which were acceptable in predicting the displacement demand of the skew bridge. Based on the parametric study, finally, the study will discuss the bridge behaviors with different skew angles and input directions of time histories.

Figure 1. Sliding/Friction Mechanism of bearings in Kuan- Lung bridge (439 Gal recorded PGA) during the Chi- Chi Earthquake.

Friction coefficient test

Experimental Setup and Test Program

Fig. 2 shows the test setup of the friction coefficient test. The dimensions of bearing specimens are limited due to (1) minimal height of 15mm can only be provided by the manufactory and (2) consistent width of 150mm for same specimens to be used in the shaking table test. As the result of these considerations, the bearing specimen is 150mm×150mm in plane and 15mm thick. The Hardness IRHD material and shape factor of the rubber is 60 and 3.75, respectively. One SS400 shim plate is placed inside of the bearing. Based on the test requirements for rubber bearings in standard specifications for highway bridges (AASHTO, 2002), twelve cases were performed including two types of bearing (RB and PTFE-RB) on two different surfaces (material: cement mortar, steel) with four sliding velocities (1.06, 50, 150 and 300 mm/sec) are considered. In each test, the bearing clamped by the restrain plates on the top beam, as shown in Fig. 2, was forced to slide on the prefixed blocks, either made by cement mortar or steel, within 14 cycles. The target displacement for horizontal actuator is 60 mm in both positive and negative direction, providing a sufficient friction length to develop sliding mechanism. The constant normal force around 4MPa for each bearing was applied by two vertical hydraulic actuators, while shear and friction force were measured through two load cells under a loading beam. The relative displacement was recorded by a temposonic sensor to compare to the data from horizontal actuator.

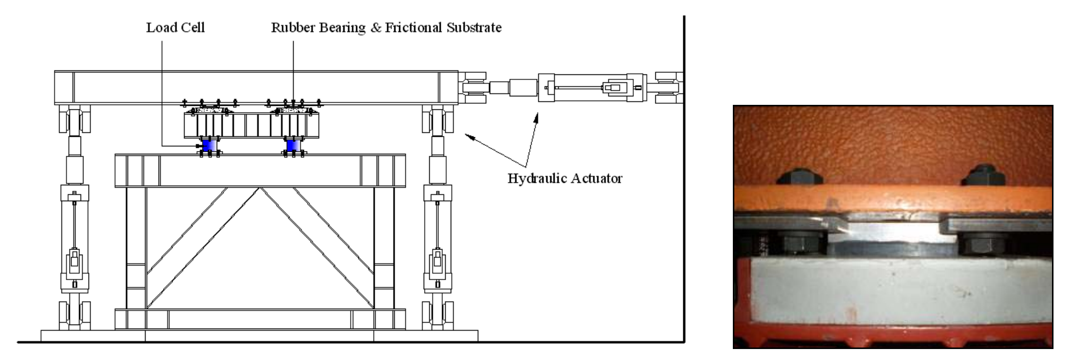


Figure 2. Test Setup of the friction coefficient test.

Test results and Discussions

The typical hysteretic loop of bearing considering sliding/friction mechanism is shown in Fig. 3. During the test, it has been found that the friction force rapidly decreases after first cycle and is getting smaller and smaller as increasing the number of cycles. There is no doubt that long accumulated sliding distance will wear bearing surface and smoothen the surface of cement mortar or steel with some residue rubber attached.

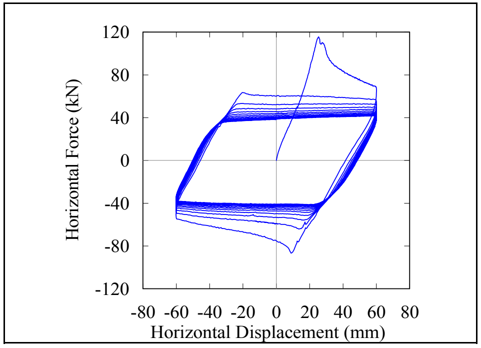


Figure 3. Typical Hysteretic loop of the friction coefficient test.

The friction coefficient was determined according to ISO 15113 (ISO 2005). Since friction force is unstable in the first three cycles and affected in the last three cycles by the horizontal actuator before stopping the test, it is suggested to neglect those six cycles to obtain the coefficient with respect to cycles. Therefore, the maximum, minimum, and average friction coefficients for each case are listed in Table 1. To reflect the construction practice of unbolted bearings, a range from 0.2 to 0.4 for the friction coefficient is more realistic than using a single value. As for the PTFE-RB, the friction coefficient from 0.1 to 0.2 can be obtained based on the test results.

Table 1. Summary of the friction coefficient test results.

Group	Friction surface	Case	Velocity (mm/sec)	Friction coefficient		
				Maximum	Minimum	Average
RB	cement mortar	1	1.06	0.378	0.346	0.358
		2	50	0.299	0.248	0.267
		3	150	0.229	0.169	0.192
		4	300	0.231	0.168	0.193
	steel plate	5	1.06	0.417	0.371	0.388
		6	50	0.536	0.422	0.467
		7	150	0.477	0.359	0.409
		8	300	0.498	0.386	0.434
PTFE-RB	steel plate	9	1.06	0.130	0.101	0.112
		10	50	0.175	0.138	0.152
		11	150	0.193	0.158	0.171
		12	300	0.213	0.172	0.188

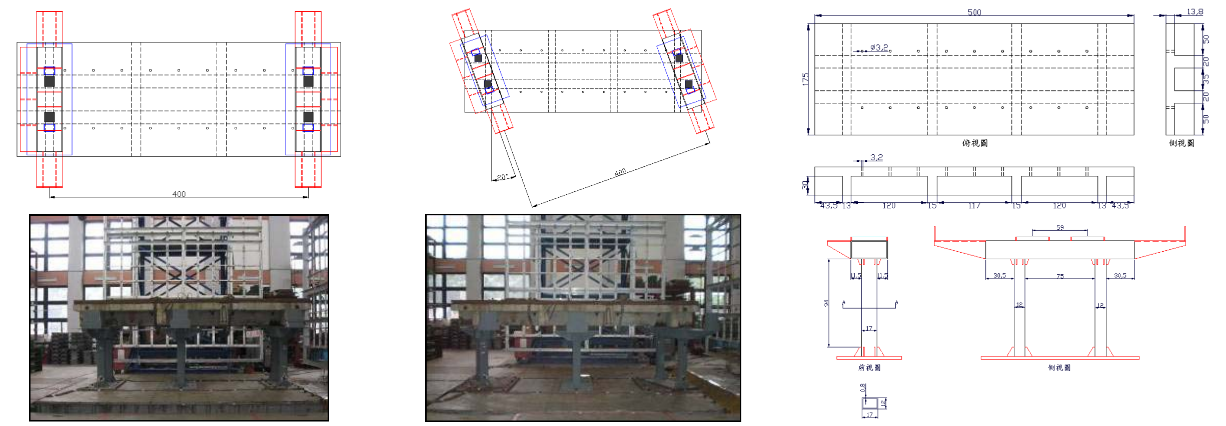
Shaking Table Test

Test specimen and setup

Shaking table tests were conducted to get realistic dynamic performance from two 1/7.5 scale-down simply-supported bridge models with rubber bearings, shown in Fig.4, a straight and a skew bridge model, respectively. Based on the definition of a complex bridge, which should be examined through dynamic analysis method (MOTC 2000), the skew angle is 20 degree. The superstructure is 10.67 tons and consists of concrete slabs, two girders and four diaphragms, supported by two rectangular hollow-section steel bents. The column bents were designed to remain elastic. The bearings used in this test are as same as in the friction coefficient test, including RB and PTFE-RB bearings. Besides, in order to compare the sliding behaviors between two different boundary conditions (B.C), both RB-RB cases which represent a semi-fixed B.C, and PTFE-RB cases which are like a roller-hinge B.C, were performed with peak ground acceleration (PGA) levels from 0.1g to 0.7g. The south bent may use RB or PTFE-RB bearing, depending upon the cases; while the north bent was equipped with RB bearing only. The input ground motion along the longitudinal direction of the bridge model is record in east-west direction of 1941 El Centro earthquake. Both time-history and response spectrum normalized to 1.0g are given in Fig.5. Regarding to the instrumentation plan, acceleration on the superstructure, relative displacement of the bearing, and surface strains at the end of the columns were measured.

Table 2. Test Schedule for the Shaking Table Test.

Bridge model	**Bearing arrangement (South end - North end)**	**Peak input ground acceleration of El Centro earthquake (g)**
Skew	RB - RB	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7
	PTFE - RB	
Straight	PTFE - RB	



(a)Straight Case (b)Skew Case (c)Bridge Components

Figure 4. Test setup of Shaking Table Test.

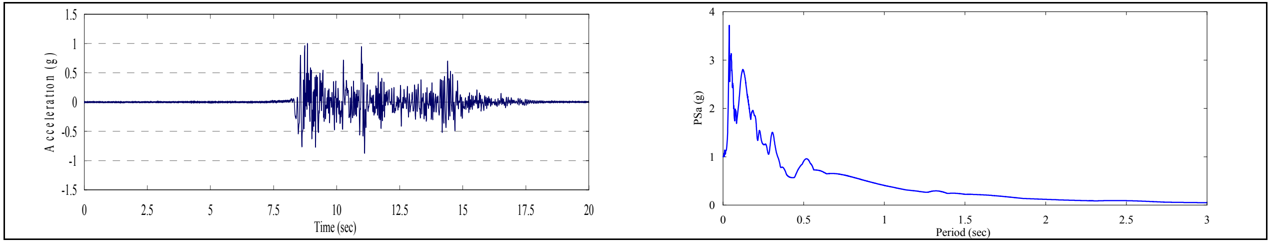
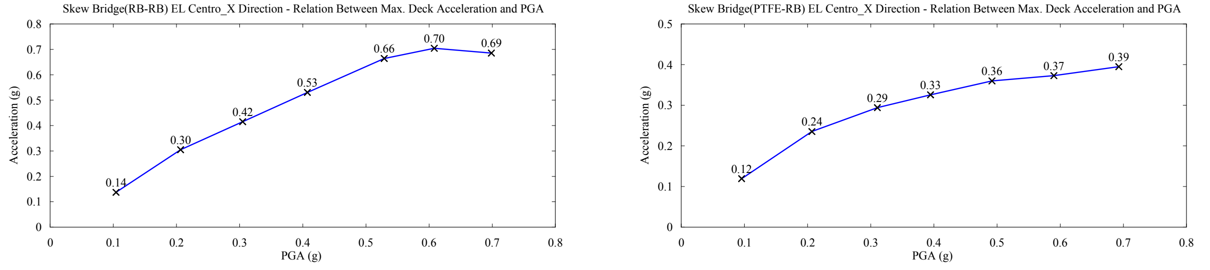


Figure 5. Input time history and response spectrum of EL-Centro earthquake.

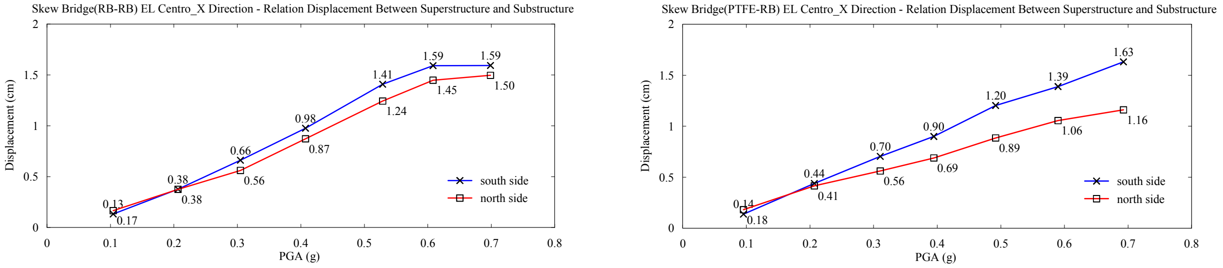
Test result

Fig. 6 illustrates the test results of peak acceleration on the superstructure with respect to PGAs. The obtained acceleration is not proportional to the PGA, not only in RB-RB case or PTFE-RB case, representing the influence of sliding effect on the global performance. Especially, the trend of the line in Fig. 6(b) is getting flat with a turning point around 0.2~0.3g. Although received same input ground motions, the accelerations in PTFE-RB case are smaller than in RB-RB case, indicating that an isolation effect is apparent when utilizing a bearing with small friction coefficient. The global structure response, particularly the force demand of the column, can re reduced due to a sliding mechanism. However, the relative displacement between superstructure and substructure is increasing. In Fig. 7(b), the obtained displacement showed no difference between two locations before PGA of 0.2g, but after that, the displacement at south bent with PTFE-RB is increasing and the displacement ratio between south and north bent is greater than 1.5. In contrast, the displacement demands at both bents in Fig. 7(a) are similar due to using same type of RB bearing to require a semi-fixed boundary condition. So, the structure performance was significantly affected by the bearing system, corresponding to a low or high friction coefficient, and the arrangement of bearings to make a specified constrain on the boundary.



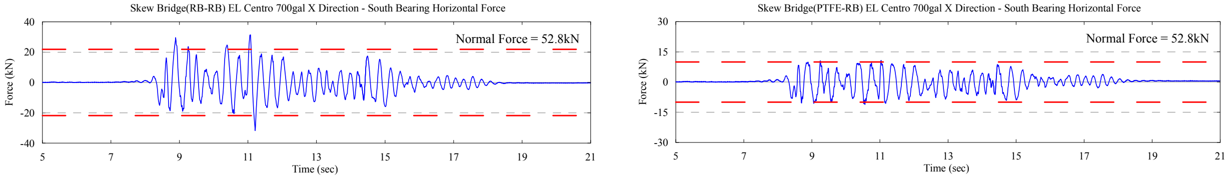
(a)RB Case (b)PTFE Case

Figure 6. Peak acceleration on the superstructure

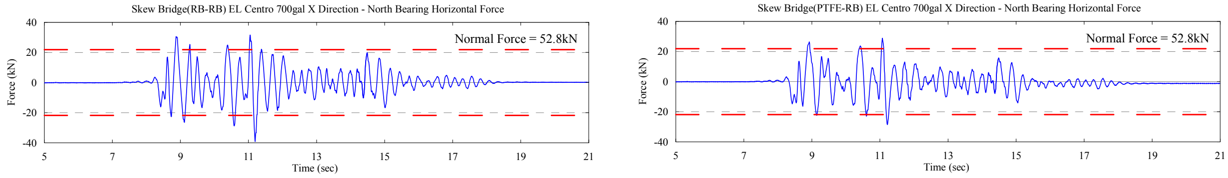


(a)RB Case (b)PTFE Case

Figure 7. Maximum relative displacement between superstructure and column bent



(a) RB-RB case (south side) (c) PTFE-RB case (south side)



(b) RB-RB case (north side) (d) PTFE-RB case (north side)

Figure 8. Column shear forces with PGA of 0.7g

So far, friction coefficient of rubber bearing was often determined through static tests under very slow velocity. However, for bridge subjected to the earthquake excitation, the coefficient from a dynamic test, such as a shaking table test, is more realistic to describe the sliding phenomena. As shown in Fig. 8, the base shear forces, which are sum of two column forces at either north or south side bent, were divided by the weight of the superstructure to determine the friction. The PGA in Fig. 8 is 0.7g, and the bridge was moved according to the recorded videos. Clearly, it is due to the sliding effect that an upper and lower bound of shear forces can be identified. The friction coefficient for RB bearing and PTFE-RB bearing is around 0.4 and 0.2, respectively, close to the test results obtained in the friction coefficient test with the speed at 300mm/sec.

Analytical simulation

Based on the structure information, both skew and straight models shown in Fig.9 were established in SAP2000 (CSI 2002) to compare the structure performance with experimental results. In order to simulate the sliding behavior of the rubber bearing, the friction-pendulum element (Wen 1976) was utilized with proper friction coefficient given from either friction coefficient test or shaking table test. Only the bearing is considered a nonlinear element with elastic shear stiffness determined by the shear modulus, area and height of the rubber, and a constant friction coefficient of 0.4 for RB bearing, as well as 0.2 for PTFE-RB bearing. In Fig. 10, the analytical models can well predict the time history of the acceleration in the cases of 0.1g, 0.4g and 0.7g, respectively. Not only the results from straight bridge model but the skew bridge models show good accuracy. Like results in Fig. 10, the comparisons regarding to displacement in skew and straight model with three PGA levels are also shown in Fig. 11. Though the time history results of displacement are not so as good as acceleration, ie., in Fig. 11 (f) the analytical residual displacement is larger than the test data; however, the peak response was capable of predicting the maximal response, helping engineers to confirm the safety of unseating length based on the design code.

Comparison and Discussion

The shear force of the substructure is resulted from the inertial force of the superstructure, cap-beam and column bents, assumed the damping force is neglectable; hence, these two loads should be identical to each other to make the loading path clearly identified through the bearing system in between. In this study, the contribution of inertial force from cap-beam and column themselves are too small to neglect because of relative small weight compared to the girder. Fig.12 represents the comparison between inertial force of the superstructure and the base shear of the substructure. The inertial force is the product of deck mass and deck acceleration at the time point corresponding to maximal acceleration of the deck; meanwhile, the base shear at the same time point was also calculated. It was found that no matter the superstructure was sliding or not, the force equilibrium relationship is satisfied in both RB-RB case and PTFE-RB case.

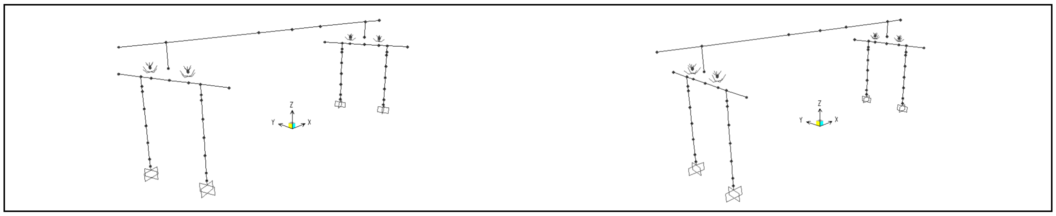
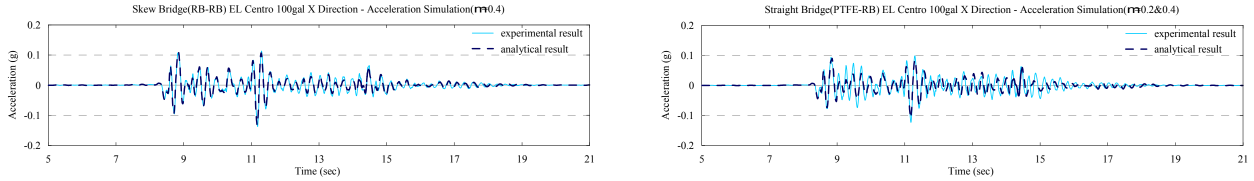
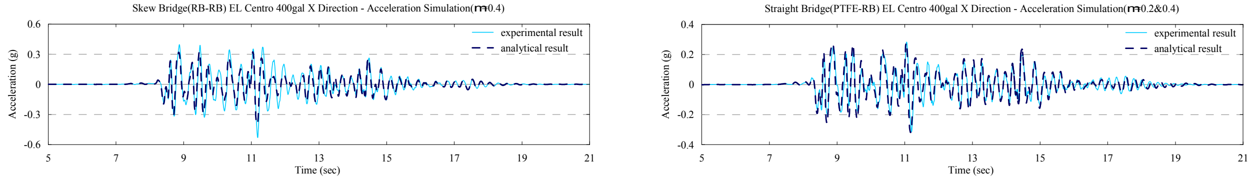


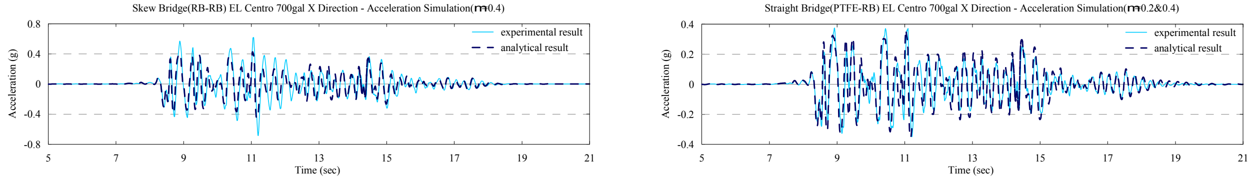
Figure 9.   Bridge Modeling (Skew case and straight case)



(a) RB-RB case (Skew bridge, 0.1g) (d) PTFE-RB case (Straight bridge, 0.1g)

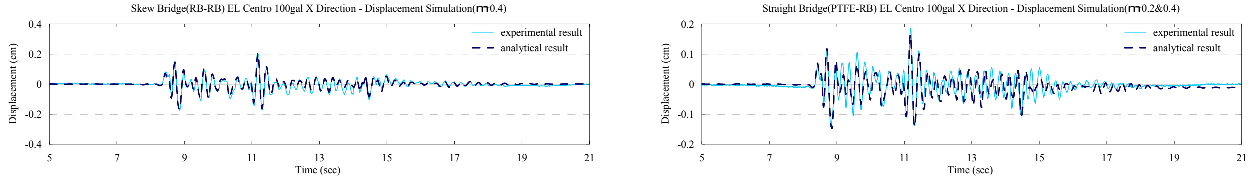


(b) RB-RB case (Skew bridge, 0.4g) (e) PTFE-RB case (Straight bridge, 0.4g)

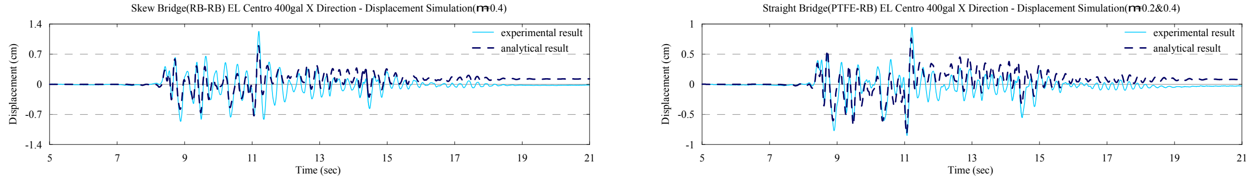


(c) RB-RB case (Skew bridge, 0.7g) (f) PTFE-RB case (Straight bridge, 0.7g)

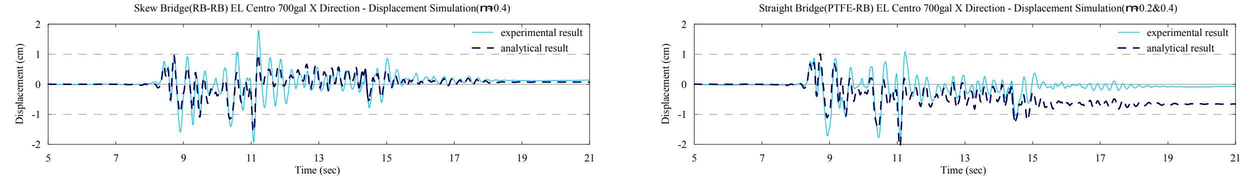
Figure 10. Comparison of deck acceleration between analytical and experimental results



(a) RB-RB case (Skew bridge, 0.1g) (d) PTFE-RB case (Straight bridge, 0.1g)



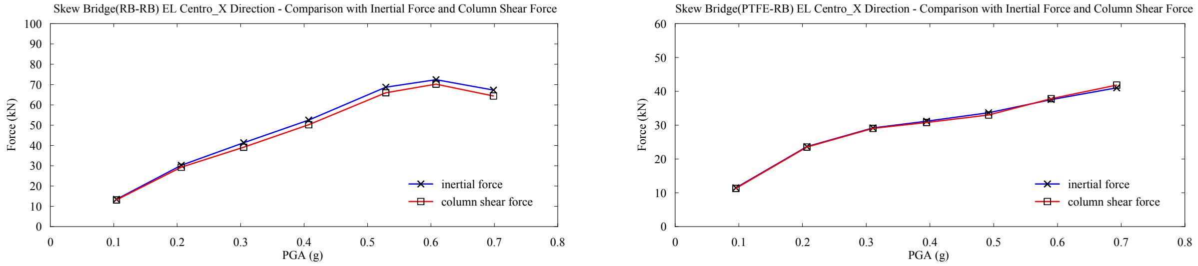
(b) RB-RB case (Skew bridge, 0.4g) (e) PTFE-RB case (Straight bridge, 0.4g)



(c) RB-RB case (Skew bridge, 0.7g) (f) PTFE-RB case (Straight bridge, 0.7g)

Figure 11. Comparison of deck displacement between analytical and experimental results

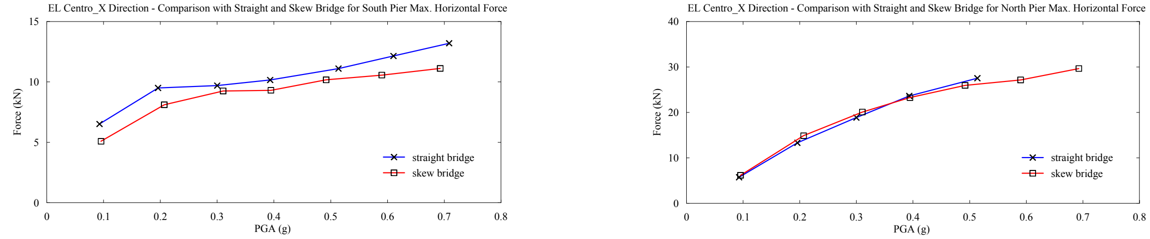
Therefore, by taking advantage of the accuracy of the analytical model, the force demand of sliding rubber bearing and columns at different PGA levels can be quickly and precisely judged. Besides, the maximal base shear force between skew and straight bridge model are also compared. As shown in Fig.13, though the force of south bent in skew bridge is slightly smaller than the force obtained from straight bridge model (Fig.13(a)), the trend of two lines almost same. However, if the skew angle is larger than 20 degree, the parametric study results in Fig.14 reveal that the structure behavior is not proportional to the skew angle with respect to different input direction of time history, especially the skew angle is larger than 20 degree. Consequently, it is suggested to use suitable bearing elements in the bridge model to obtain complex response of a skew bridge with large skew angle.



RB-RB case

PTFE-RB case

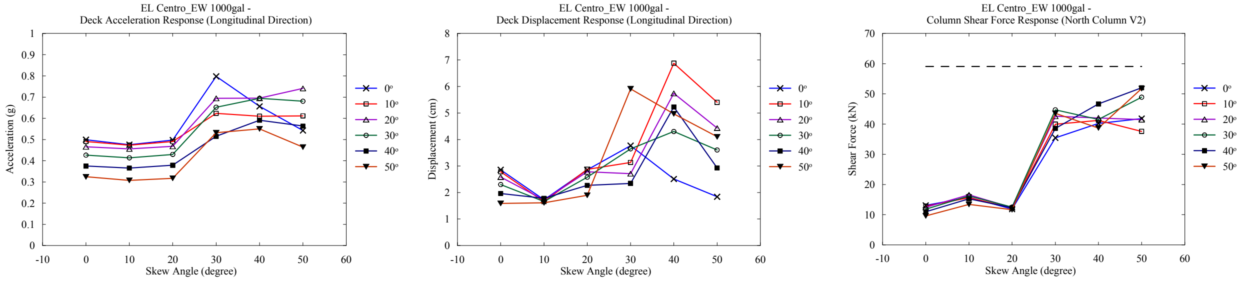
Figure 12. Comparison of inertial force and base shear force in skew bridge model



South Bent

North Bent

Figure 13. Comparison of maximal base shear force in the longitudinal direction (PTFE-RB case)



(a) Deck Acceleration

(b) Deck Displacement

(c) North Bent Base Shear

Figure 14. Prediction of maximal response for RB-RB case under different skew angles and input directions of time histories (PGA = 1.0g).

Conclusions

Based on the experimental results and the parameter studies of non-linear finite element analysis, the following conclusions may be deduced:

(1) The construction practices of rubber bearing without any anchor bolts provide a fusing mechanism for rubber bearing to slide on the bearing pad and thereafter to reduce the force demand of the column and enlarge the displacement requirement of seat width.

(2) A series of friction coefficient was conducted first and followed by shaking table tests on two scale-down skew bridge models. According to the experimental results, the friction coefficient for RB and PTFE-RB bearing is 0.4 and 0.2, respectively, considering the influence of high speed may be required in a real seismic event.

(3) The seismic responses of a skew bridge are not proportional to different skew angle and different input direction of time history. Due to the complex responses of skew bridge with large skew angle under intense ground motion, the use of nonlinear modeling for the rubber bearings is recommended especially for important bridges.

Acknowledgments

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